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The Use of Statistical Process Control in Deep Space Network Operations

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May 15, 2002

ABSTRACT

This report describes how the Deep Space Mission System (DSMS) Operations Program Office at the Jet Propulsion Laboratory's (JPL) uses Statistical Process Control (SPC) to monitor performance and evaluate initiatives for improving processes on the National Aeronautics and Space Administration's (NASA) Deep Space Network (DSN). Background is provided on how using subjective parameters were previously used to evaluate DSN performance, and how these evaluations led to nonproductive analysis because variation in the monthly parameters was not well understood. Several of the parameters are explained, along with how SPC charts are now used to determine whether the monthly values reflect a significant change in performance, or whether the changes are within the limits of common-cause variation exhibited by the overall process. The operational definitions provided by the charts are described, as are the use of the Western Electric Zone Rules. Several examples of how the charts were used to determine the effectiveness of process improvements are also presented.

SPC provides the information required for evaluating the capability of a process and is also discussed. This information is valuable for making decisions on whether capital investments should be made to improve data collection and delivery systems. Information is also provided on how SPC was implemented on the DSN with a modest investment, by using an existing problem reporting system and archival scheduling information. The methodology described in this report can be used to comply with section 8 of the ISO quality systems standard Q9001-2000, Monitoring and Measurement of Processes. The examples also show that SPC can be used in a service environment as well as in a manufacturing environment.

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

TABLE OF CONTENTS

ABSTRACT	ii
LIST OF FIGURES	iv
SUMMARY	1
BACKGROUND	1
HISTORICAL PERFORMANCE MEASURES.....	1
INTRODUCTION OF SPC.....	2
PROCESS IMPROVEMENT	4
NEW USES OF SPC	4
CONCLUSIONS	5
LIST OF REFERENCES	12

LIST OF FIGURES

FIGURE 1: DSN TELEMETRY AVAILABILITY6

FIGURE 2: DSN TELEMETRY FUNCTIONAL AVAILABILITY7

FIGURE 3: SUPPORT PRODUCT DISCREPANCY REPORTS8

FIGURE 4: SUPPORT PRODUCT DISCREPANCY REPORTS REVISED9

FIGURE 5: VLBI FUNCTIONAL AVAILABILITY10

FIGURE 6: VLBI FUNCTIONAL AVAILABILITY REVISED.....11

Summary

The Deep Space Mission System (DSMS) Operations Program Office at the Jet Propulsion Laboratory (JPL) uses statistical process control (SPC) to determine how well the NASA Deep Space Network (DSN) meets committed performance, and for evaluating continuous improvement efforts.

DSN Operations collects performance data on each instance of providing telecommunications services and conducting ground based science observations. This information is stored in two databases and is later retrieved for monthly performance analysis and interpretation. A database of the scheduling history contains temporal information on each tracking period. The information in this database includes the customer being supported, the activity name, the equipment configuration required to provide the support, and the day and time that the support was provided. The second database, the discrepancy reporting management system (DRMS), is used to document problems that occur during tracking periods. Data from both databases are analyzed and interpreted using an SPC software package for determining monthly, overall system-availability values for each committed data type, and to monitor those processes for which DSN Operations has direct responsibility. These processes include operation of the Deep Space Stations (DSS) and their associated data systems during service instances, and non-real time support services. Non-real time support services include the generation of operations documentation and other data products that the link controllers and data systems use to provide tracking services.

SPC has also proven to be an important and cost-effective tool for evaluating whether changes made to improve processes are successful, by providing clear, objective statistical signals associated with changes in performance. More recent uses of SPC include the monitoring of tracking and data system performance, to determine whether new deliveries of software and hardware by DSMS Engineering have a positive or negative impact on functional availability.

Although relatively new on the DSN, the use of SPC is being expanded to other disciplines as part of an overall initiative to improve the processes that DSN Operations uses for capturing and delivering science and engineering data to Network customers.

Background

The NASA DSN, operated by the California Institute of Technology, is a worldwide space flight tracking network consisting of three equidistantly spaced Deep Space Communications Complexes (DSCC) and a Network Operations Control Center (NOCC) located at the laboratory. The DSCCs are located in Goldstone, California, Canberra, Australia, and Madrid, Spain. Each complex has several parabolic antennas that are 26, 34, and 70 meters in diameter. Each antenna size, or subnetwork, is specifically designed to provide telecommunications services to HEO spacecraft, interplanetary spacecraft, or both. These services include the radiation of commands, the reception of telemetry, and the generation of radio metric data used for spacecraft navigation. Science services are also provided, and include radar imaging from the Goldstone Solar System Radar (GSSR), and the generation of radio science, radio astronomy, and very long baseline interferometry (VLBI) data. The Network operates 24 hours per day, 365 days per year.

The DSMS Operations Program Office within the Interplanetary Network Directorate is programmatically responsible for operating and maintaining the DSN for NASA. Within this office, Consolidated Space Operations Contract (CSOC) personnel, contracted by the Space Operations Management Office (SOMO) in Houston, Texas, provide support services for the complexes. These services include support product generation, operations documentation, logistics, engineering change management activities, and operations and maintenance of the NOCC.

Historical Performance Measurements

Prior to 1997, DSN Operations provided a monthly summary of performance parameters to NASA Headquarters. The parameters covered several areas, and were selected to provide an overall

indication of how well the Network was performing its mission. They included the availability of the Network to provide telemetry, radio metric, and command capability, three of the six data types committed to customers. The availability number was derived from data that were collected and archived in a discrepancy reporting management system (DRMS) and a scheduling history database. The DRMS is used to report problems during tracking support periods. DRs are written whenever a customer is not satisfied with the service, a problem prevents committed service or data from being provided, or a problem causes a customer to deviate from their original sequence and incur extra work. Each discrepancy report (DR) includes the affected data type, the amount of data that was lost, degraded, or recovered, the project being supported, the deep space station (DSS) providing the support, the system and subsystem where the suspected failure occurred, the suspected cause, a description of the incident, and other ancillary information. The scheduling history database is an archive of the 7-day operations schedules published each week, and represents the schedule of events on the Network for all antennas and facilities. Each record identifies the flight project or ground based observer, the supporting antenna, the committed data types, the subsystems required for support, the beginning and ending times of the support period, and a brief description of the activity. The availability number, expressed as a percentage, is computed by,

$$Availability = \frac{T_s - T_l}{T_s} \times 100$$

where T_s is the total time all antennas and associated systems are scheduled to provide service and T_l is the time lost due to problems that preempted service as recorded in DRs. A 12-month, moving run chart was used to depict and report the availability as shown in Figure 1.

Prior to presenting each report, DSN Operations Management used the run chart to determine whether there had been any significant change in performance from the previous month. If a value “looked low” and it was anticipated that questions would be asked about what might be causing poor performance, additional time was spent researching which systems and or causes had contributed to most of the data loss, and specific failures that were unusually long were identified for discussion. These evaluations were very subjective and usually led to no conclusions as to whether there were any systematic problems underlying a particular month’s performance, or whether a low value indicated common-cause variation in numerous factors and causes that could affect Network-level performance. This method of evaluation was also not capable providing a baseline of performance that could be used to evaluate performance improvement initiatives.

Introduction of SPC

In 1997, NASA directed its field centers to become registered with the ISO and to move to a service oriented business model. In response to that directive, JPL initiated process-based management and began preparing for ISO 9001 registration. Just prior to this time, JPL had just completed training all employees in Total Quality Management (TQM) techniques. During that training period, DSN Operations had become interested in SPC methods, but had not yet instituted any program to use the methodology for monitoring performance or evaluating improvement efforts. To qualify for ISO registration, element 23 of ISO 9001 requires that statistical methods be used to monitor processes that affect quality. Operations recognized that this provided both the incentive and an opportunity to conduct a trial use of the SPC methodology in both areas.

Since the availability parameters were already being reported each month, it was decided to build upon the existing reporting infrastructure and processes. This approach represented a minimum investment and provided an opportunity to evaluate the use of SPC within the new service-based

environment. If the system proved successful, management anticipated that SPC could not only be used to monitor the effectiveness of process improvement efforts in Operations, but also the effect of engineering change orders (ECO) on the performance of tracking and data systems.

Shewhart's control charts are the primary tools used to implement SPC. They provide the operational definition rules for making decisions when interpreting the charted data (1, p 262). It was decided that the availability of several commercial software applications provided the most cost effective method to generate the charts. Although some practitioners in the manufacturing sector still recommend having production personnel manually construct the charts, the DSN architecture and environment did not easily lend itself to this method. There were two reasons for this. First, the string of equipment used contains globally assigned instances of some assemblies. Second, multiple operators are involved. Both of these factors compound the number of charts that would be required to an unimaginable number.

The SPC software Quality Analyst (QA), offered by Northwest Analytical, was selected from among several available applications. The software could produce several types of control charts, automatically indicate violations of the Western Electric zone rules, and allow design requirements or specification limits to be included on the charts. It also provided other statistical tools used for data organization, evaluation, and interpretation. These tools included various diagrams for determining whether a process was stable, had a reasonable probability distribution, and that would indicate the capability of the process being evaluated. The data available from the DRMS and the scheduling history database, along with the processes and procedures already in place to provide the monthly management reports, provided a cost-effective method of implementing the system, with only a small investment in the QA software and time required to manipulate the data. In addition, since the data in the databases represented the population, sampling would not be required.

Most of the data used in the charts were available from the databases in Microsoft Excel format. This enabled a simple transfer of the data into the spreadsheet format of QA software. Since an extensive history was available, it was also possible to determine baseline performance values for each process.

The QA software was capable of generating several types of control charts, but for a wide variety of situations Wheeler recommends individuals and moving range XmR (IR in QA terminology) charts. These are particularly suited to population data and are statistically valid for several probability distributions (1, p. 134). He also notes that XmR charts are also valid for counts, measurements, ratios, and percentages (2, p. 16).

The DSN global availability for telemetry delivery is shown in Figure 2. The first 24 data points, corresponding to monthly performance values in the history data for 1996 through 1997, were used to determine the mean and calculate the 3- σ limits. These limits are indicated on the charts as the *ucl* (upper control limit) and the *lcl* (lower control limit). The *cl* or central line represents the mean. The functional availability specification is also shown on the charts. The software is configured to indicate out-of-control conditions using the Western Electric Zone rules, where data points denoted by asterisks indicate violations within the *ucl* and *lcl* (see appendix X), and data points denoted by pound signs indicate violations outside the 3 σ process control limits.

The functional availability specification, depicted on the charts as *LSL* (lower specification limit), is the engineering specification for the percentage of scheduled time an antenna and all associated subsystems are designed to deliver data (3, p. 42). This value is determined from reliability data for each subsystem and assembly in the delivery chain. For example, a single antenna and all associated end-to-end equipment required for telemetry delivery should be available 98% of the time it is scheduled for support. This includes losses for hardware and software failures. As depicted on the chart, the Network as a whole is shown as capable of meeting the functional availability requirement. Although the charts provide an overall performance value that can be used for an indication of the state of the entire Network, it cannot and should not be used for evaluating quality improvement efforts.

Since the noise or common variation is additive, any significant change in the performance of one delivery chain—an antenna and associated equipment—will not be discernable in the aggregate noise, except for changes that affect all delivery chains. For quality improvement efforts targeted for a specific subnetwork or sub-process, non-aggregated data must be used.

With a good operational definition, management could objectively monitor the performance of the Network and determine if a significant change in performance was occurring and that warranted further investigation, or whether a performance value was within the common variation of the overall system and that further investigation would waste resources. The next step was to expand the use of the charts to include process improvement efforts.

Process Improvement

An example of how the charts provide evaluative criteria for process improvement is in the area of support product generation. Support products include pointing predictions for antennas, receivers, telemetry data systems, the metric data assembly, and also the sequence of events (SOE) provided by the projects and ground based observers for each tracking pass.

Figure 3 represents the performance of the process used to generate and deliver the support products to the Network. As shown on the chart, the baseline performance is a mean of 11 monthly DRs written against the process. CSOC began an effort in early 1999 to cross train personnel and to improve written procedures used for generating the support products. The data shows that several months later, after they had revised the procedures and completed the training program, there was a significant drop in problems. The rule violation indicated by the asterisk at the last data point shows that May of 1999 as the beginning of the improvement.

The chart was then modified to begin calculating the mean performance and process limits from May 1999. The revised chart, shown in Figure 4, indicates that the new mean is approximately 4. This is better than a 100% decrease in average number of problems each month and represents the new baseline of performance against which other improvement initiatives will be judged. One of the advantages of the XmR chart is that short runs still provide reasonable control limits.

New Uses of SPC

The successful use of SPC to objectively monitor performance and evaluate process improvement within DSN Operations as represented by the examples described above are seen by management as only the beginning of a broader program. The use of process control charts is still being explored. This has already been accomplished in some areas. For example, the mean time between failures (MTBF) is now being explored for each antenna. Since the Network comprises several different antenna types with varying architecture, the disaggregation of the data to the antenna level can point to not only performance differences among individual assets, but to performance differences among antenna types, or subnetworks. SPC data is also being used at the system level for determining how new software deliveries or hardware upgrades affect performance. The DR information for failures within a subsystem is available and provides information on the number, frequency, and nature of the failures. The performance charts will indicate if the baseline has improved or degraded following each installation. An example of this use is the recently redesigned VLBI system.

In 2000, the Interplanetary Network and Information Systems Directorate, now the Interplanetary Network Directorate, decided to invest in and redesign the VLBI system and use it as an independent validation of Doppler and ranging navigation methods, and to improve navigation accuracy for Mars missions. Figure 5 shows the historical performance of the system, which had been originally designed in the early 1980s. The mean availability of the system indicated on the chart is approximately 96%. However, it was not capable of meeting its specified functional availability specification of 92%. This is evidenced by the *lcl* falling below the LSL. The capability index of the system at that time was,

$$C_{pk} = \frac{DNS}{3\sigma} = \frac{95.7 - 92}{95.7 - 88.3} = \frac{3.7}{7.4} = 0.5$$

where DNS is the distance to the nearest specification, and the standard deviation is calculated from the control chart. Since the recommended capability index of a good system is 1.3 or greater, significant improvements would have to be made that would raise the mean functional availability, or the common variation would have to be significantly reduced.

The original VLBI system design had been based on an architecture that was predominantly analog. This included radio frequency (RF) down-conversion equipment and the use of magnetic tape for storage and data delivery. This equipment required periodic alignment and calibration, and due to its complexity did not perform to the availability levels of other DSN systems. Since that time, advances in digital signal processing became available and afforded an opportunity to simplify overall design and eliminate resource-intensive calibration and maintenance activities, while improving system reliability and availability.

The new system was introduced in early 2000 and the performance was monitored using the old system's control chart and baseline performance level. Zone rule violations on the process control chart, indicates that the system immediately exhibited monthly performance that exceeded that of the older system. The system is also now capable of meeting the functional availability specification, since the capability index is now,

$$C_{pk} = \frac{DNS}{3\sigma} = \frac{98.3 - 92}{98.3 - 94.2} = \frac{6.3}{4.1} = 1.54$$

Although the new system has not been officially transferred to Operations, but has been remotely operated by DSMS Engineering personnel to show proof of concept and to evaluate the performance of the design, management is highly confident that it will easily meet design specifications, show a savings in maintenance costs, and also provide a higher functional availability.

Conclusions

SPC has proven to be a valuable tool not only for monitoring Network-wide performance on the DSN, but also for validating the effectiveness of changes made in operations and engineering, intended to improve the Networks ability to provide maximum data collection and delivery to its customers. Unlike previous attempts to characterize performance, the use of SPC ensures that decisions are based on data that reflect verifiable changes in performance levels, and not on subjective impressions. SPC was also implemented with a modest investment in money and resources, because the methodology was integrated into an existing problem reporting process, combined with information from an existing history database.

DSN Operations now uses SPC to gauge the effectiveness improvements to its own sub-processes and has also begun to provide feedback to engineering on the effect of engineering changes made to the Network's architecture. This is an ongoing process, and new ways of using SPC methodology are still being explored. These include deploying the use of control charts to other aspects of operations and maintenance at a lower level that will contribute to continuous improvement and the Network's overall effectiveness in performing its mission.

Figure 1

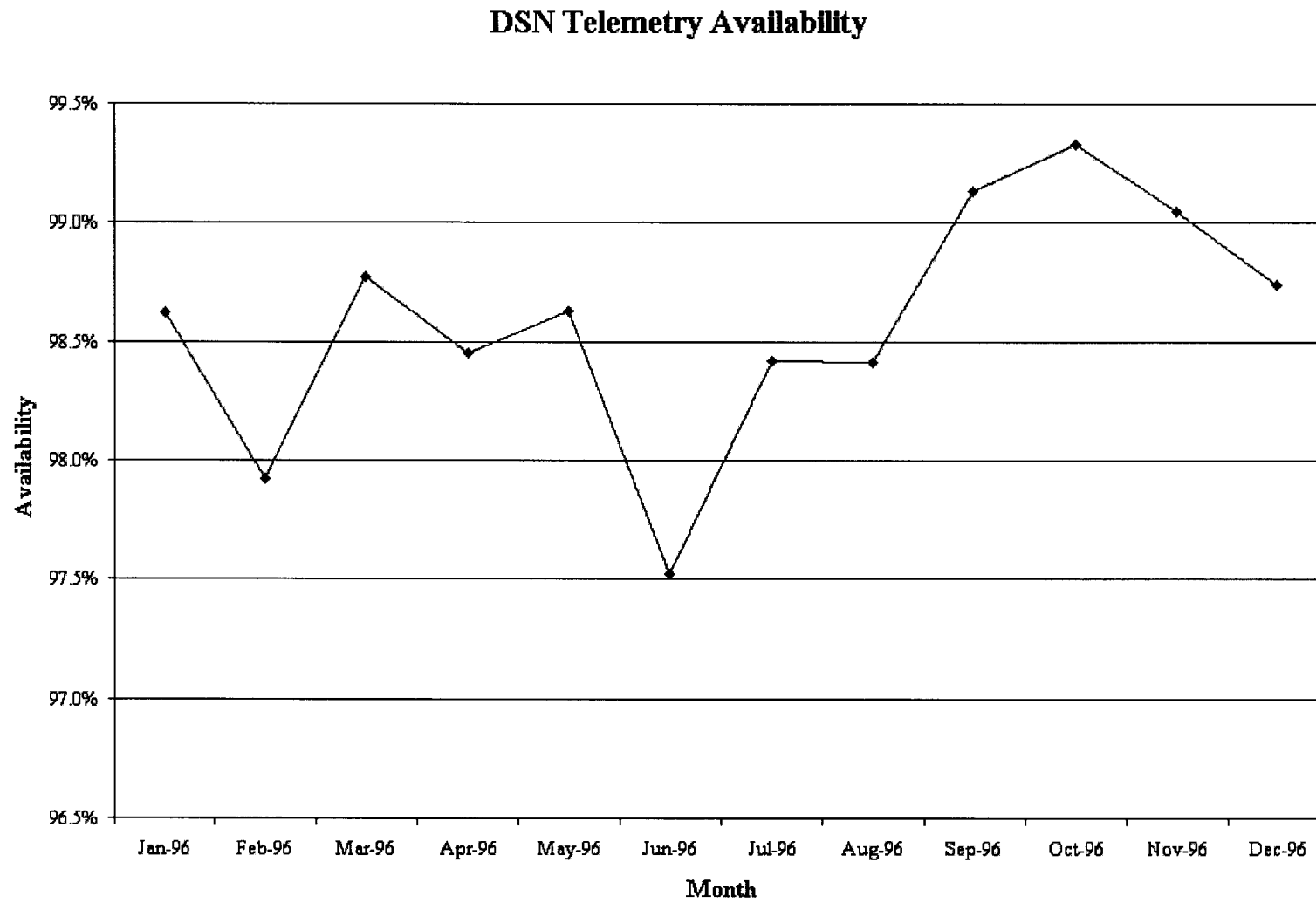


Figure 2

4/30/02 File: NETTLM.DAT
Deep Space Network
Telemetry Functional Availability

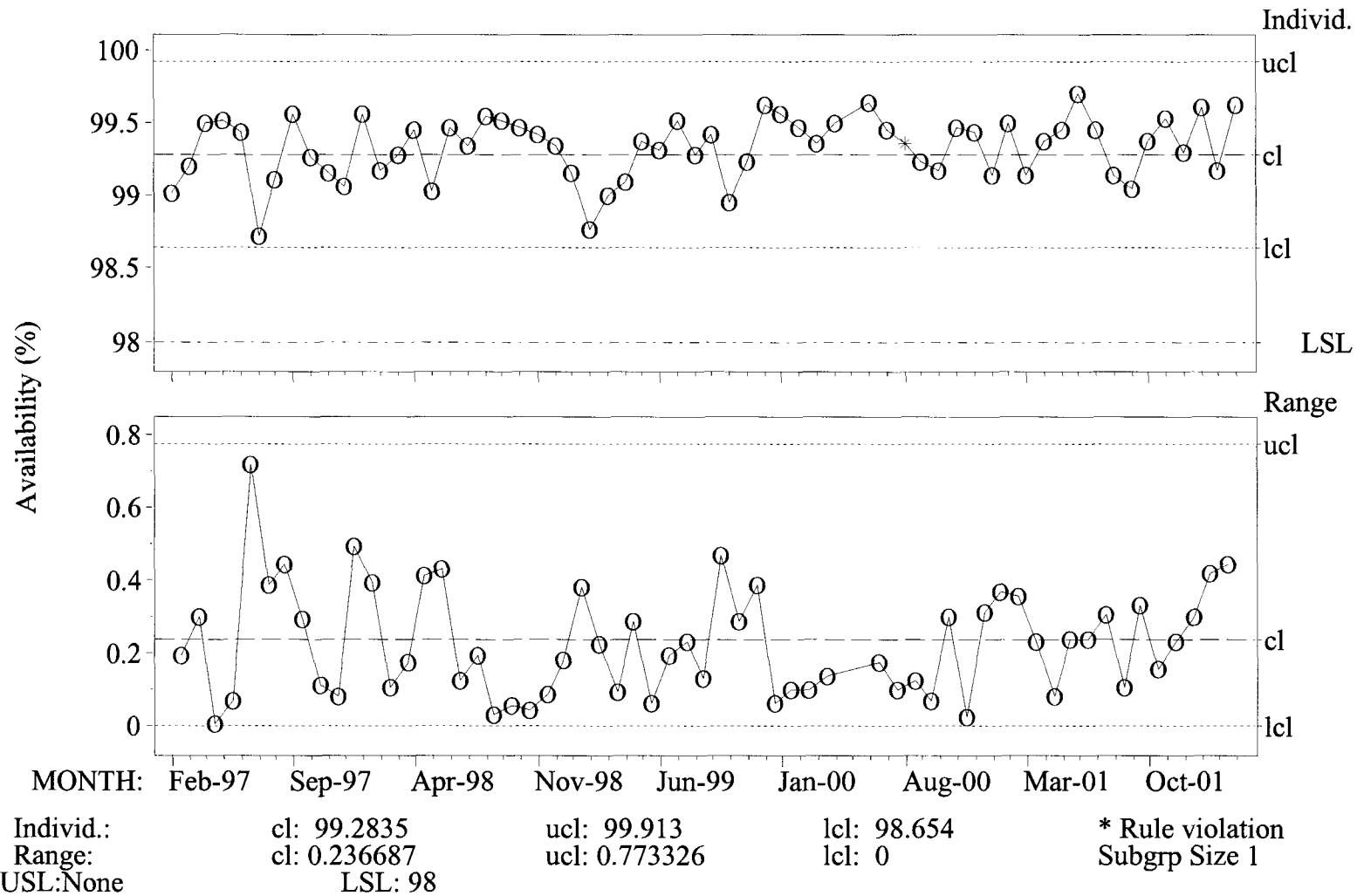


Figure 3

5/1/02 File: SVE2.DAT
SVE Metrics; Quality
Support Product DRs

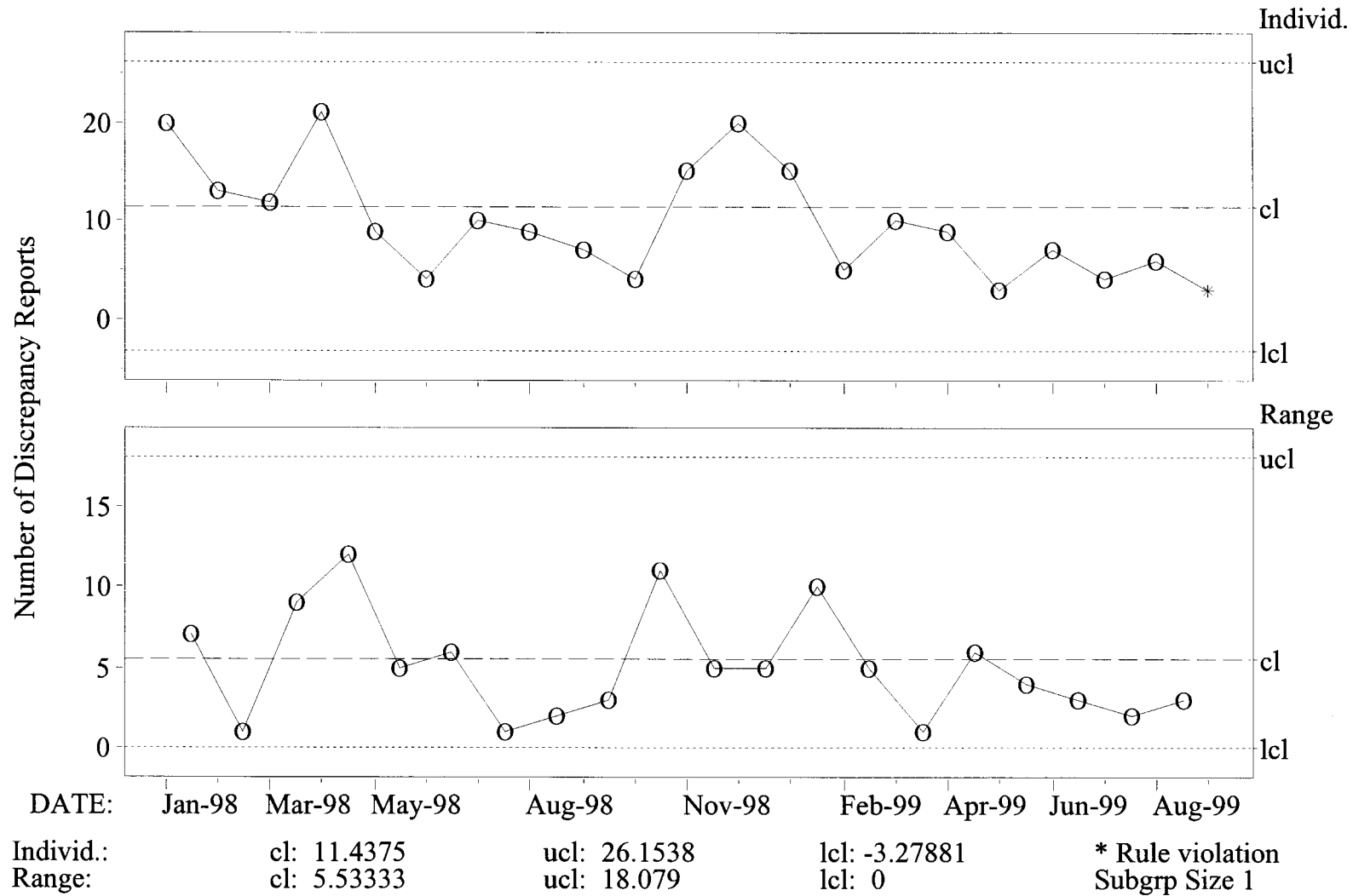
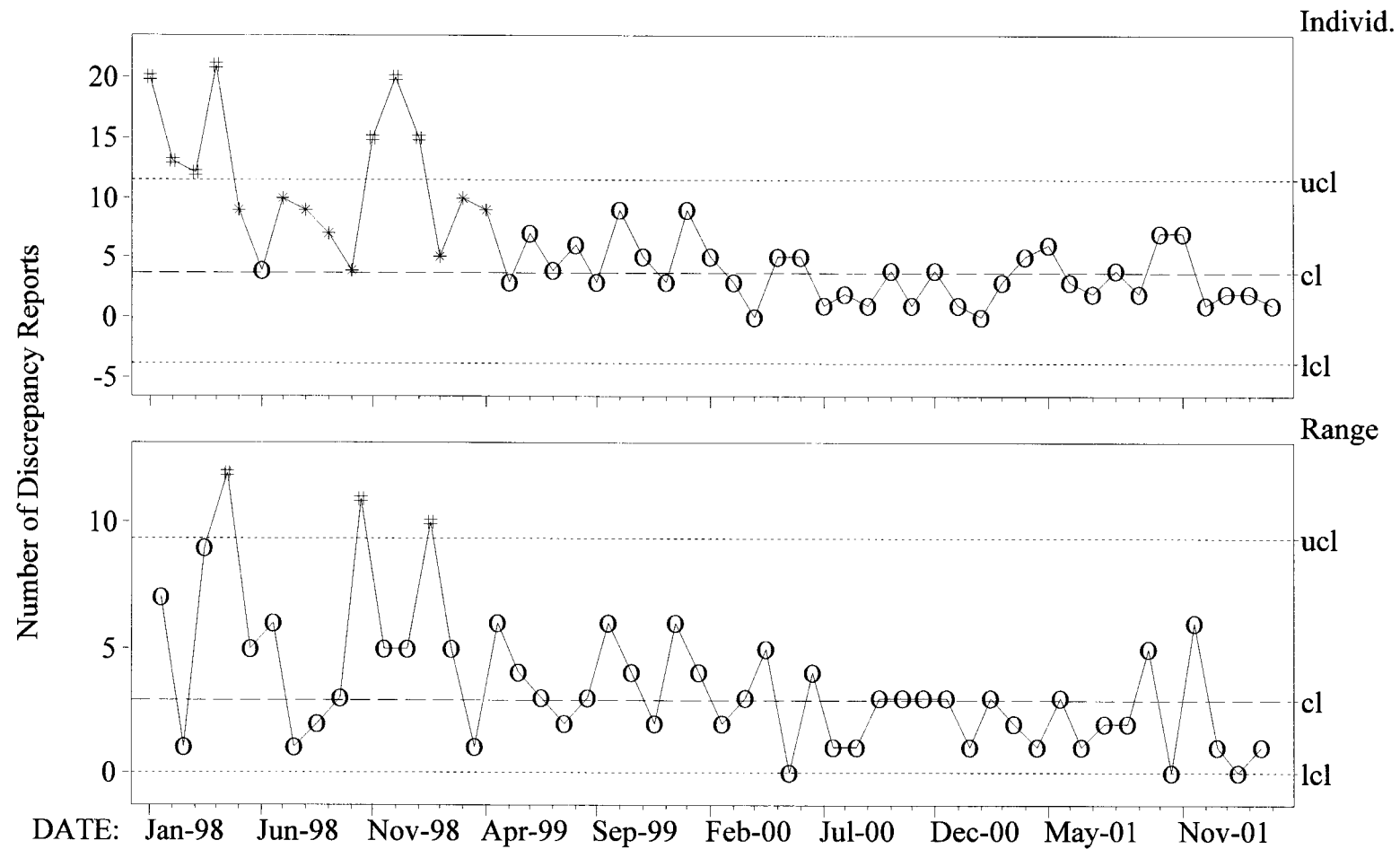


Figure 4

4/30/02 File: SVE2.DAT
SVE Metrics; Quality
Support Product DRs



Individ.: cl: 3.8 ucl: 11.4463 lcl: -3.84628 * Rule violation
 Range: cl: 2.875 ucl: 9.39345 lcl: 0 Subgrp Size 1

Figure 5

4/30/02 File: NETVLBI.DAT
DSN VLBI Availability
VLBI Functional Availability

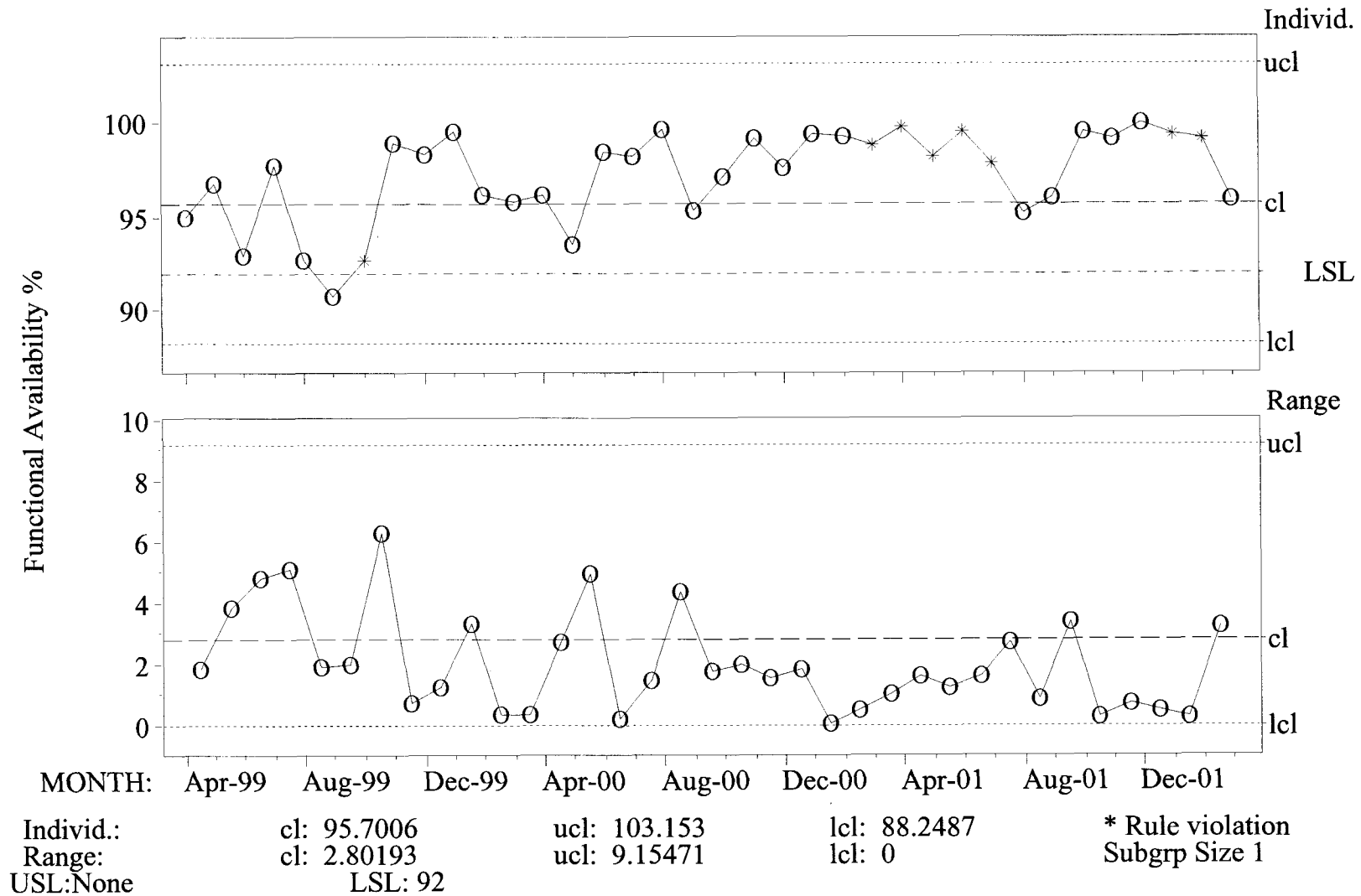
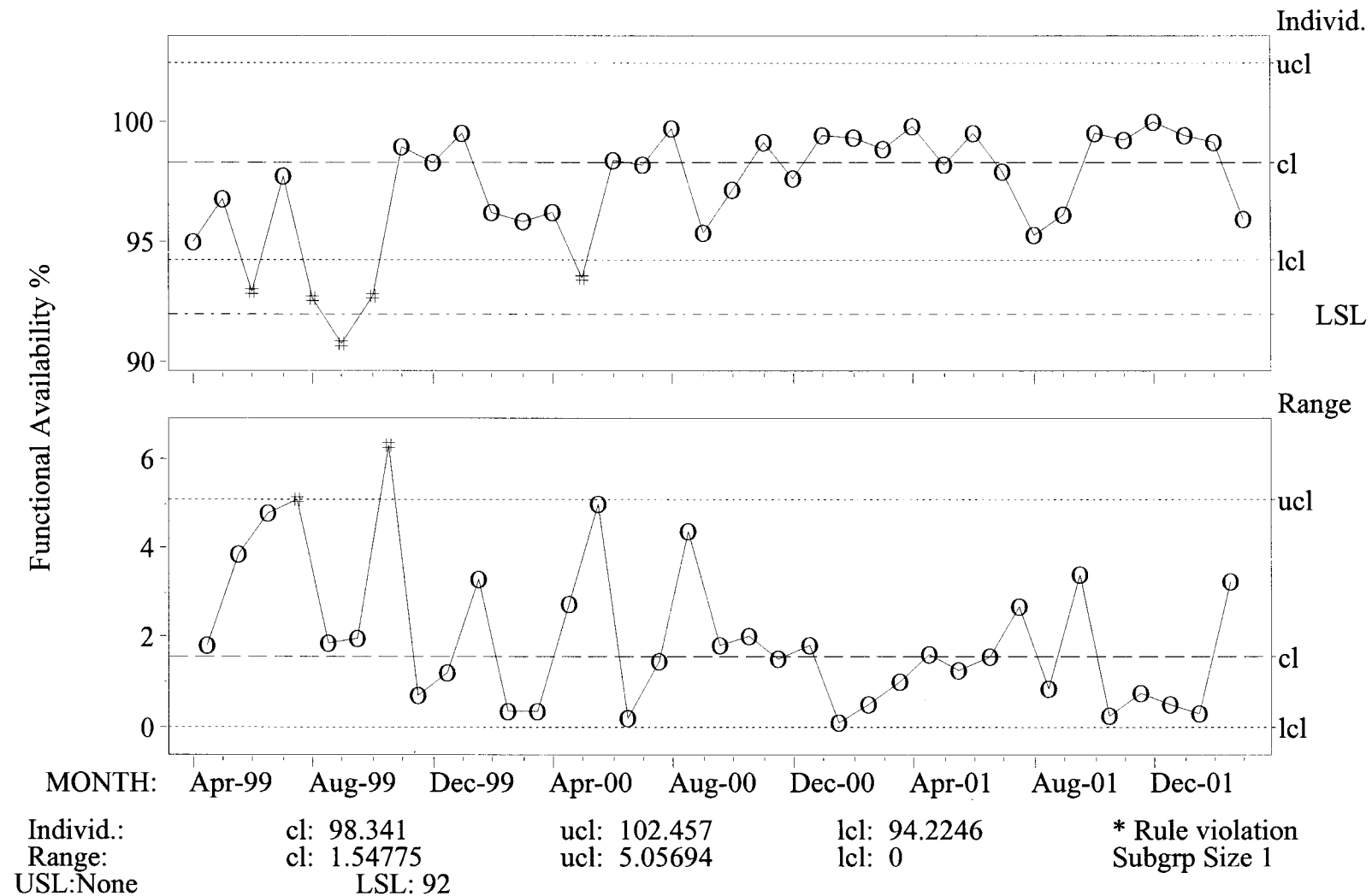


Figure 6

4/30/02 File: NETVLBI.DAT
DSN VLBI Availability
VLBI Functional Availability



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